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Effectiveness of Two Forecast Models for Stratiform Precipitation

by Jeffrey E. Passner

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14. ABSTRACT

The U.S. Army Research Laboratory has developed a mesoscale model, the Battlescale Forecast Model (BFM), which is a hydrostatic model designed for boundary-layer applications for the Army. Using the basic assumption of Sundqvist in 1989, the model determines precipitation rates by the density of clouds. Since ARL receives 15-km Mesoscale Model Version 5 (MM5) output from the Air Force Weather Agency, it was decided to study the skill in forecasting stratiform precipitation, precipitation rates, biases, and precipitation types from both the BFM and MM5. The precipitation type forecast is a post-processed routine developed by ARL and is used for both models. Results of this study during the winter months of 2003 showed that both models forecast much weaker precipitation rates for snow than rain although the models do well differentiating between rain and snow.

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Mesoscale, precipitation, BFM, MM5

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Preface

The Integrated Meteorological System (IMETS) is a weather data system utilized by the Air Force weather forecasters in support of Army operations. Prediction and forecast products on IMETS are achieved through the Battlescale Forecast Model (BFM) and the Fifth-Generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5), which are used for short-term and long-term forecasts, respectively. Both models provide precipitation forecasts although different techniques have been derived to provide precipitation output. This report describes the precipitation-forecasting techniques and a comparison of the BFM and MM5 products.

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Summary

The U.S. Army Research Laboratory has developed a mesoscale weather model called the Battlescale Forecast Model (BFM). After model initialization, the BFM produces forecast variables for a 24-h period. Since the Army required a longer-term prediction, the Mesoscale Model Version 5 (MM5) gridded data are received from the U.S. Air Force Weather Agency to provide forecast information for up to a 48-h period. Due to the importance of precipitation on the tactical decision aids, as well as military operations in general, both models forecast stratiform and convective precipitation, which are made available to the user in a database and graphically.

This report describes the basic meteorological theory applied to the precipitation processes and forecasts for both the BFM and MM5. The effectiveness of the BFM and MM5 precipitation output are analyzed as well.

Precipitation forecasts are derived from numerical model data, such as the BFM and MM5. These data provide the forecaster and users with a detailed overview of the atmospheric conditions that might produce precipitation along with the general precipitation rates, amounts, and types. These precipitation parameters are later placed into a database so other programs, such as the Integrated Weather Effects Decision Aid, can attain this information.

1. Introduction

The Integrated Meteorological System (IMETS) is a mobile, operational, automated weather data receiving, processing, and disseminating system utilized by Air Force weather forecasters in support of Army operations. The U.S. Army Research Laboratory (ARL) is supporting the forecaster to make more specific and precise battlefield weather forecasts by producing weather products on IMETS. One product to assist in short-term forecasting (<=24 h) is an operational mesoscale model, the Battlescale Forecast Model (BFM). For longer-term data, the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model Version 5 (MM5) output is available from 6 to 48 hours (*1*, *2*).

The BFM produces many forecasting parameters, including temperature, pressure, dew point, relative humidity, and windspeed and direction as well as precipitation amounts. While these outputs provide valuable weather information, Tactical Decision Aids (TDAs) such as the Integrated Weather Effects Decisions Aid (IWEDA), have a need for additional precipitation parameters such as precipitation rates and precipitation types. The IWEDA has been developed to simplify the manner in which environmental impacts on weather systems are displayed to users. The IWEDA generates current and forecasted impacts on personnel and approximately 70 weapon systems, such as attack helicopters and fixed wing aircraft. Both the BFM and the MM5 can be used to derive precipitation amounts and rates, while a post-processing software package has been developed to forecast precipitation types using the model-derived output (*3*).

2. Mesoscale Models for the Army

The ARL implemented the Higher Order Turbulence Model for Atmospheric Circulation (HOTMAC) as their model for the IMETS platform in response to the Army's requirement for small-scale weather information on the order of less than 500 by 500 km. The HOTMAC was selected because it is numerically stable at long-time steps, globally relocatable, emphasizes boundary-layer physics, and is platform-independent. In an effort to keep the model run time as fast as possible, the BFM contains no convective cloud parameterization or cloud microphysics package. The model currently is run to 24 h; however, due to military requirements, it was necessary to add the MM5 to the IMETS platform to provide forecast grids out to 48 h from the initial forecast time (*4*, *5*).

2.1 The BFM

The BFM contains 16 terrain-following vertical levels, a model top of 7000 m above the highest elevation, a 10-km horizontal resolution, and a log-linear stagger so that there is greater vertical resolution near the surface. The rapid run time for the model can be attributed to a single nest and no moist physics or cumulus parameterization routines. However, because of the implicit approach, time steps on the order of 200 s (at 10-km resolution) are common for typical atmospheric advective speeds and vertical motion fields in the model. Soil temperature on five subsurface levels is solved using the heat conduction equation, while long and shortwave radiation within a single layer for a stratus cloud is calculated using the method of Hanson and Derr. The basic variables that are prognostically forecasted by the model are perturbation potential temperature, total water substance mixing ratio, wind speed, wind direction, pressure, soil temperature, turbulence kinetic energy and length scale, and non-convective precipitation rate (*6*, *7*).

To initialize the BFM, surface data and upper-air observations are input into the model in the area of interest. Additionally, the 36-h forecasted Naval Operational Global Atmospheric Prediction System (NOGAPS) package, which is issued by the Air Force Weather Agency (AFWA) via the Air Force Automated Weather Distribution System, is utilized as the long-range data that the BFM is nudged toward. The NOGAPS grid points are spaced 1º apart, both latitude and longitude, on the mandatory pressure surfaces. Lateral and time-dependent boundary conditions (large-scale forcing) are supplied from grid-point data close to the area of interest taken from NOGAPS output valid at analysis and forecast times of interest.

The BFM-generated outputs for the grid include the u and v horizontal wind vector components, potential temperature, and water vapor mixing ratio. These forecast fields are saved at 0, 3, 6, 9, 12, 15, 18, 21, and 24 h from the base time of the model run and placed into a Gridded Meteorological Data Base (GMDB).

2.2 The MM5

The MM5 is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation.

Terrestrial and isobaric meteorological data are horizontally interpolated from a latitude-longitude mesh to a variable high-resolution domain on Mercator, Lambert Conformal, or polar stereographic projection. Since the interpolation does not provide mesoscale detail, these interpolated data may be enhanced with observations from the standard network of surface and rawinsonde stations using either a Cressman or multiquadric scheme. In the MM5, there is also a program that performs the vertical interpolation from pressure levels to sigma coordinates. The sigma surfaces near the ground closely follow the terrain, while the higher-level sigma

surfaces tend to approximate isobaric surfaces. Additionally, the MM5 has a flexible and multiple nesting capability, advanced physical parameterization, 3-D data assimilation system via nudging, and it can be run on various platforms (*8*).

Version 3 of the MM5 was used for this study; it is from AFWA and has a resolution of 15 km mesh data on 41 vertical levels. The ARL receives these MM5 data in gridded binary form for the Continental United States twice each day, which are initialized at 0600 universal time coordinated (UTC) and 1800 UTC, respectively. Due to computational and processing constraints, there is a 6-h stagger between the initialization valid time of the 15-km mesh and the first forecast output, thus the first MM5 forecast is a 6-h forecast. The frequency of the model output is every 3 h, for a time period of 48 h.

The current AFWA operational version of MM5 places the lowest model vertical level at 20 magl. To generate data at the standard observation heights of 10 magl and 2 magl, similarity theory is being used at ARL to extrapolate to these lower levels from the lowest MM5 sigma level. In this fashion, temperature, dew point, and wind data at levels 2 magl and 10 magl are produced at ARL in addition to the 41 MM5 sigma levels of data.

The parameterizations selected by AFWA with this version of the MM5 are as follows:

- **Grell cumulus parameterization** − Designed for grid sizes of 10 to 30 km, this parameterization accounts for subgridscale convection and compensating subsidence.
- **MRF planetary boundary-layer model** − Parameterizes the mixture of heat, moisture, and momentum in the boundary layer.
- **Reisner mixed phase explicit moisture microphysics** − Cloud and rainwater fields and ice processes are predicted explicitly. No graupel or riming processes are calculated.
- **Dudhia cloud radiation** − Provides solar and infrared fluxes at the ground and atmospheric tendencies resulting from the radiative processes.
- **MM5 five-layer soil model –** Temperature predicted in 1, 2, 4, 8, 16 cm layers with fixed substrate below using vertical diffusion equation.

3. Cloud Condensation and Non-Convective Precipitation from the BFM

The relative humidity of each of the 16 layers produced by the BFM is one key parameter needed to calculate the precipitation amount and precipitation rates in the BFM. Since the BFM does not directly calculate the relative humidity; it was necessary to derive this value using eq 1:

$$RH = \frac{TWTR}{SWVAP} \tag{1}$$

where

RH = relative humidity for each grid point

TWTR = total water at each grid point

SWVAP = saturation vapor pressure for the grid point

These calculations are done for each of the 16 levels at each BFM grid point.

3.1 Total Liquid Water and Cloud Fractions

In the BFM, the mixing ratio of total water is a combination of the mixing ratio of water vapor and the mixing ratio of cloud water as noted in eq 2:

$$Q_w = Q_v + Q_c \tag{2}$$

where

Q_w = mixing ratio of total water

Q_v = mixing ratio of water vapor

Q_c = mixing ratio of cloud water

The value of Q_v, the mixing ratio of the water vapor, is derived from the initial data of the model. In model operation, Q_c is initially 0.

Recalling that the change of total water with time is conserved, the approach suggested by Sommeria and Deardoff is used to derive the value of Q_c, the mixing ratio of cloud water (*9*).

The liquid water potential temperature is defined as:

$$\theta_l = \theta - \frac{\theta}{T}\frac{L_v}{C_p}Q_c \tag{3}$$

where

θ_l = liquid water potential temperature

θ = potential temperature

T = absolute temperature

L_v = latent heat of condensation

C_p = specific heat of dry air at constant pressure

In order to recover the potential (or absolute) temperature and mixing ratios of water vapor (Q_v), the probability density function, G, defined by Sommeria and Deardoff (*9*), is used. The density function is assumed to be Gaussian such that:

$$G = \frac{1}{2\pi\sigma_{\theta}\sigma_{qw}\left(1-r^2\right)^{1/2}} \exp\left[-\frac{1}{\left(1-r^2\right)}\left(\frac{\theta_l^2}{2\sigma_{\theta}^2} - r\frac{\theta_l q_w}{\sigma_{\theta_l}\sigma_{qw}} + \frac{q_w^2}{2\sigma_{qw}^2}\right)\right] \tag{4}$$

where

θ_l = fluctuation of liquid water potential temperature

q_w = fluctuation of total water mixing ratio

and:

$$\sigma_{\theta\ell} = \overline{\theta_\ell^2} \tag{5}$$

$$\sigma_{qw}^2 = \overline{q_w^2} \tag{6}$$

$$r = \frac{\overline{\theta_l q_w}}{\sigma_{\theta l}\sigma_{qw}} \tag{7}$$

The local condensation is given by:

$$Q_\ell = \left(Q_w - Q_s\right) * H\left(x\right) \tag{8}$$

where

Q_s = the saturation mixing ratio,

H(x) = Heaviside function,

x = Q_w-Q_s

defined as:

$$H(x) = 0, \quad x<0 \tag{9}$$

$$H(x) = 1, \quad x>0$$

The final equation for cloud water mixing ratio is expressed as:

$$Q_c = 2\sigma_s\left[RQ_l + \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{Q_l^2}{2}\right)\right] \tag{10}$$

where

R = cloud fraction

$$Q_l = a\,\frac{\Delta Q}{2\sigma_s} \tag{11}$$

where

$\Delta Q = Q_w - Q_{sl}$

$$\sigma_s^2 = 1/4(a^2\overline{q_w^2} - 2ab\overline{q_w\theta_l} + b^2\overline{\theta_l^2}) \tag{12}$$

The values of a and b in eq 12 are constants as defined in Yamada (*10*) while the value of R in eq 10 is a function of cloud coverage for a given volume of air as given by Mellor (*11*).

Figure 1 shows how the cloud fraction R varies as a function of Q_l, a statistical ratio of super or subsaturation. In the figure, clouds can exist even if the mixing ratio of water vapor over a grid is not saturated. This is realistic since the grid spacing normally used in mesoscale models is larger than the size of small clouds.

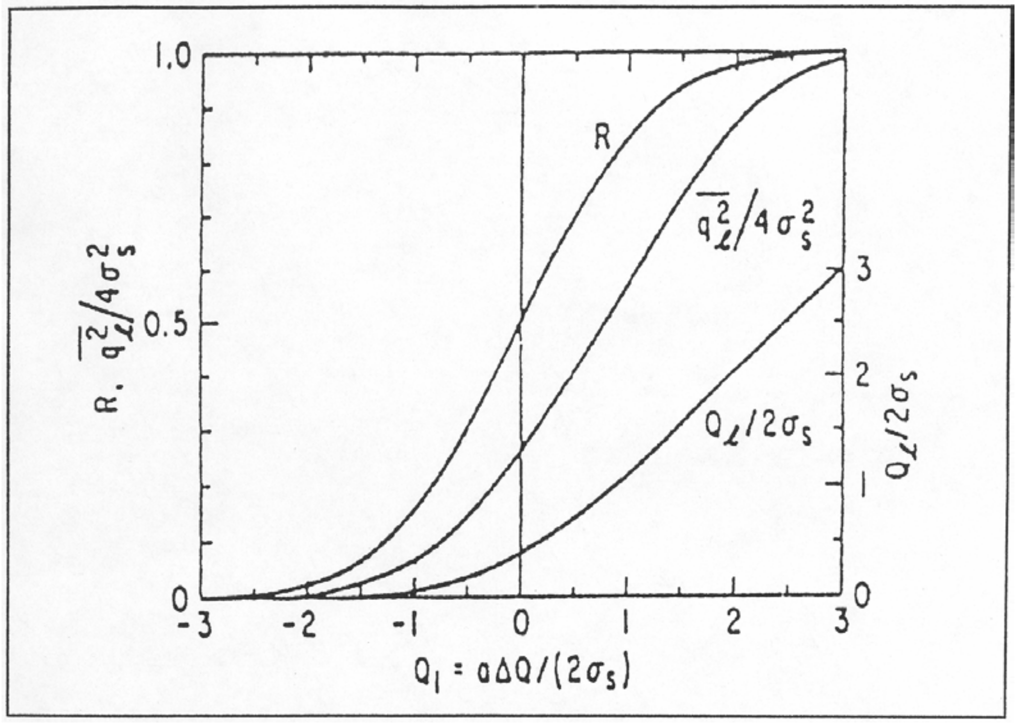

Figure 1. Relationship Showing the Cloud Fraction as a Statistical Function.

However, after investigating this method for cloud fractions it was determined that it was not an effective way to calculate clouds. Some of the reasons for this decision included:

- The value of cloud liquid water is often too low due to the coarse resolution in both the horizontal and vertical in the BFM.
- Saturation is not well represented in the sounding data used for initialization of the BFM.
- The BFM nudges to forecasted NOGAPS data, which contains its own biases.
- Original design of the BFM was for stratiform precipitation in the lowest 4 km.
- The assumption that the grid spacing is larger than the size of the smaller clouds may be accurate; however, stratiform clouds are often in layers and are larger.
- The Sommeria and Deardorff (*9*) method to derive cloud fractions was not designed for mid-levels or for multiple-layer cases.
- The technique developed by Sommeria and Deardorff (*9*) was designed for much smaller grid volumes than the current BFM.

Ironically, the statistical cloud model was a method formulated to avoid coarse grid models in which the saturation values are lowered arbitrarily to compensate for the cloud that was not

resolved; however, the technique of training or "learning" of the data did provide much more realistic and accurate cloud fractions in the BFM. While it may appear that small differences in relative humidities are not important, Walcek proved that a 2 to 3 percent increase in relative humidity could lead to a 15 percent increase in cover. Additionally, Shultz and Politovich observed that relative humidity values in excess of 55 percent between 500 to 1000 mbar usually identify regions with widespread cloudiness on the Nested Grid Model (*12*, *13*).

The BFM also had this bias, with clouds observed in layers well below saturation. To compensate for this, Passner developed a routine based on a set of IF-THEN rules with an emphasis on season, time of day, location, and layer relative humidity. This cloud program was used on both the BFM and MM5 with statistical evaluation showing the software to be most effective in the lowest 4000 ft of the atmosphere (*14*).

The importance of the cloud fraction is seen in the next section when discussing the precipitation rates produced by the BFM.

3.2 Precipitation Rates from the BFM

Since the microphysical processes of stratiform precipitation are not part of the BFM, the stratiform precipitation is parameterized as a function of cloud liquid water. The scheme formulated by Sundqvist et al. for stratiform precipitation is used in the BFM (*15*).

The rate of release of precipitation is described by:

$$P = C_o Q_c \left[1 - \exp\left(- \left(\frac{Q_c}{R * Q_{c,cr}} \right)^2 \right) \right] \tag{13}$$

where

C_o = characteristic time for the conversion of cloud droplets into raindrops

Q_c = mixing ratio of cloud water content

R = cloud fraction

$Q_{c,cr}$ = Cloud water content, at which release of precipitation starts to be efficient

According to Sundqvist (*15*), $Q_{c,cr}$ should have a value typical of individual cloud types and be invariant to grid resolution. He also suggests a value of 0.0001 for C_o, which equates to a conversion time of approximately 167 min. In his study, Sundqvist worked with the operational fine mesh model of the Norwegian Meteorological Institute, which uses a horizontal grid resolution of 50 km. In this test, for the BFM, a value of 0.0004 (42-min conversion rate) was

employed for the model runs. This value, C_o, was found to be one of the more influential values in determining the accumulated precipitation.

The rate of precipitation P, at a given z^* level, is given by:

$$P_r\left(z^*\right)=\left(\frac{\overline{H}+z_{g\,max}-z_g}{\overline{\overline{H}}}\right)\int_{z^*}^{\overline{H}}\rho(z^*)Pdz^* \tag{14}$$

where

z^* = vertical coordinate system used in the BFM

H = depth of the model atmosphere

Z_{gmax} = highest terrain elevation in the BFM domain

Z_g = terrain elevation

P = air density

To simulate the coalescence process, Sundqvist et al (*15*) introduced an additional parameter, which increases with the rate of precipitation. Additionally, when the temperature is lower than -5 °C, to simulate an enhanced release of precipitation in clouds containing a mixture of droplets and ice crystals (Bergeron-Findeisen mechanism), he adds another parameter. Finally, since cirrus clouds contain mainly ice crystal growth by diffusion, Sundqvist uses another parameter that increases with decreasing temperature.

In the stratiform case, evaporation of precipitating water is assumed to take place according to the relation:

$$E_r = k_E(1-U)(1-CF)\sqrt{P_r} \tag{15}$$

where

k_E = is a coefficient in the expression for evaporation of precipitation (0.00001 in this case)

U = relative humidity of the layer

CF = cloud fraction for the grid volume

$\sqrt{P_r}$ = precipitation rate

The final form of the stratiform precipitation rate at the surface is:

$$P_r(0) = \left(\frac{\overline{H} + z_{g\max} - z_g}{\overline{H}}\right)\frac{1}{\rho_w}\int_0^{\overline{H}} \rho(z^*) C_{OF} Q_C(z^*)\left[1 - \exp\left(-\left(\frac{Q_c(z^*)}{CF * Q_{(c,cr)F}}\right)^{1/2}\right)dz^*\right] \tag{16}$$

where

C_{OF} = Parameter to include Bergeron-Findeisen mechanism for precipitation formation

ρ_w = density of water

The subscript F in the term $Q_{(c,cr)F}$ indicates that the additional parameter for the coalescence and Bergeron-Findeisen mechanism are included. The final precipitation rate is expressed in millimeter per hour.

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4. Precipitation Rate from the MM5

The MM5 has many different ways to treat precipitation physics. The explicit schemes treat resolved precipitation physics while implicit schemes treat the non-resolved precipitation physics. In the MM5 version being discussed here, the explicit scheme is used with the Reisner mixed-phase ice scheme. The scheme is activated whenever grid-scale saturation is reached. The equations for water vapor, cloud water (ice), and rain water (snow) mixing ratios are based on the conservation of moisture but add the effects of the Reisner microphysics package. An example of these equations, the equation for rain water (snow if below 0 °C) mixing ratio, is:

$$\frac{\partial p^* q_r}{\partial t} = -m^2\left[\frac{\partial \frac{p^* u q_r}{m}}{\partial x} + \frac{\partial \frac{p^* v q_r}{m}}{\partial y}\right] - \frac{\partial p^* q_r \dot{\sigma}}{\partial \sigma} + \delta_{nh} q_r DIV - \frac{\partial V_f \rho g q_r}{\partial \sigma} + p^*\left(P_{RE} + P_{RC} + P_{RA} + P_{SM} + P_{CI}\right) + D_{qc} \tag{17}$$

where

m = map factor

p^* = p star

q_r = mixing ratio of cloud water

σ = sigma

δ_{nh} = non-hydrostatic constant

DIV = divergence

V_f = fall speed of rain or snow

ρ = density of air

G = acceleration of gravity

P_{RE} = the evaporation of rain and sublimination/deposition of snow

P_{RC} = conversion of cloud to rain (ice to snow)

P_{RA} = accretion of cloud by rain (ice by snow)

D_{qc} = diffusion term

P_{SM} = snow melt

P_{CI} = heterogeneous freezing of cloud water to cloud ice

The terms P_{SM} and P_{CI} are the two terms added to the simple ice phase scheme. In the Reisner scheme, snow does not melt instantaneously above 0 °C. Additionally, supercooled water can exist below 0 °C and unmelted snow can exist above 0 °C. Separate arrays are used to store vapor, cloud, cloud ice, and snow.

The mixing ratio of rain water is used as a key parameter in the fall speed term, which determines the rainfall rate at the surface. The equation for the fall speed is:

$$V_f = a \frac{\Gamma(4+b)}{6} \lambda^{-b} \tag{18}$$

where

V_f = fall speed

Γ = gamma function

a = 841.9946 for rain or 11.72 for snow

b = 0.8 for rain or 0.41 for snow

The value of λ from eq 18 is determined in eq 19:

$$\lambda = \left(\frac{\pi N_o \rho_w}{\rho q_r} \right)^{1/4} \tag{19}$$

where

π = 3.1416

N_o = Marshall-Palmer intercept parameter $8x10^6$ m^{-4}

ρ = mean air density of rain or snow particles (1000 and 100 kg m^{-3})

5. Statistical Evaluation of Mesoscale Models and Precipitation

Two types of evaluations are done in this study. The first will be for "YES/NO" forecasts, where the forecast provides information if a certain weather phenomena will or will not occur. A second type of evaluation is where the model output is investigated for "error" or how much the predicted value differs from the observed value.

5.1. Evaluation of "YES/NO" Forecasts

A contingency table provides a statistical method to display answers to binary YES/NO forecasts. Some evaluation techniques include the probability of detection (POD), false alarm rate (FAR), the correct non-event (CNE), critical success index (CSI), true skill score (TSS), and bias. The calculations are based on the contingency elements listed in table 1, while the equations for the evaluation techniques are also shown.

Table 1. Contingency Table for Forecasted and Observed Weather Event.

	Forecast YES	**Forecast NO**
Observed YES	A	B
Observed NO	C	D

$$POD = \frac{A}{A + B} \tag{20}$$

$$\mathrm{FAR} = \frac{\mathrm{C}}{\mathrm{C} + \mathrm{A}} \tag{21}$$

$$CNE = \frac{D}{D + C} \tag{22}$$

Donaldson developed the CSI, which considers three of the four elements in the contingency table; however, it does not take into account the D element (null element). Hanseen and Kuipers formulated an equation that does factor in the null event, and called it the TSS (*16*, *17*).

$$\mathrm{CSI} = \frac{\mathrm{A}}{\mathrm{A} + \mathrm{B} + \mathrm{C}} \tag{23}$$

$$TSS = \frac{(AD) - (BC)}{(A + B)(C + D)} \tag{24}$$

The bias in a forecast is the ratio of the number of positive forecasts to the number of observed events, as shown in eq 25:

$$Bias = \frac{A + C}{A + B} \tag{25}$$

5.2 Error Evaluation

The three main products used in this study to evaluate model or post-processed derived output are mean absolute difference (AD), root-mean square error (RMSE), and correlation coefficient (CC). The equations are:

$$AD = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} | x_{o,i,j} - x_{p,i,j} |}{m * n} \tag{26}$$

where

X = meteorological variable

O = observation

P = prediction of variable

i = i^{th} surface station

j = j^{th} forecast day

n = number of stations,

m = total number of forecast days

Small values of AD are related to good agreements between observation and forecast.

$$RMSE = \sqrt{\frac{\sum_{j=1}^{m} \sum_{i=1}^{n} \left(x_{o,i,j} - x_{p,i,j}\right)^2}{m * n}} \tag{27}$$

The values of RMSE are proportional to those of the AD. The CC is displayed in eq 28. The CC measures the strength of the relationship between two variables. When CC >0, it indicates a positive linear relationship. A value of 1.00 indicates a "perfect" correlation between the observed and predicted values of a meteorological forecast.

$$CC = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} x_{o,i,j} * x_{p,i,j}}{\sqrt{\sum_{j=1}^{m} \sum_{i=1}^{n} x^2_{o,i,j} * \sum_{j=1}^{m} \sum_{i=1}^{n} x^2_{p,i,j}}} \tag{28}$$

---

6. Evaluation of Precipitation Forecasts

There were approximately 25 model runs done in a variety of locations in the United States; however, there was an emphasis on typical wintertime cases and stratiform precipitation since the main goal was to study precipitation rates, precipitation type, and the resulting surface visibility.

To verify these data, hourly surface observations were randomly used at a variety of unique terrain locations on the grid. This was done so that the influence of terrain could be included on the resulting precipitation totals. Each hourly surface observation includes a coded value for the accumulated precipitation over the past hour. Unfortunately, the precipitation rates produced by the BFM are instantaneous rates, such as 0.06 in/hr, while the MM5 rates are an average rate determined by the total precipitation output from the model over a 3-h period. Assumptions must be made that the model precipitation is a steady rate, which may be a safe assumption for stratiform precipitation, although stratiform precipitation can vary with time. An effort was

made to eliminate all convective precipitation cases in this study. This is not always feasible as even the most uniform storms sometimes contain mesoscale features that can enhance precipitation on smaller scales.

6.1 Results of the BFM and MM5 Precipitation Forecasts

The most basic evaluation of the model precipitation forecasts was to investigate how well the model forecasted precipitation at any hour of the model runs. Table 2 displays these data.

Table 2. "YES/NO" Forecasts of Precipitation During the Winter Season in 2003.

Model Precip	**BFM**	**MM5**
Samples	501	463
POD	0.66	0.82
FAR	0.35	0.42
CNE	0.79	0.70
CSI	0.48	0.51
TSS	0.45	0.52
Bias	1.02	1.42
Cases with precip	37%	33%

The results indicate that the MM5 has a higher POD of forecasting precipitation, although it does have a slightly higher FAR and is biased toward overforecasting precipitation. The BFM data set does have a slightly higher percentage of cases with precipitation, although this difference is not significant enough to bias the results.

6.2 Precipitation Rates

It is impossible to derive the instantaneous precipitation from a surface observation; therefore, the precipitation rates, as already mentioned, are not exactly matched. However, these data in tables 3 and 4 do give the user a valuable glimpse of rainfall intensity from the models.

Table 3. Statistical Analysis of Precipitation Rates from the BFM.

BFM hours	Samples	RMSE (mm/h)	CC	Fcst Ave (mm/h)	Observed Ave (mm/h)
00	31	3.87	0.12	0.38	1.81
3	22	1.43	0.15	0.56	1.01
6	26	2.36	0.42	0.63	1.18
9	22	1.40	0.09	0.65	1.13
12	17	1.74	-0.15	0.67	1.05
>12	30	1.28	-0.05	0.61	0.85
Totals	148	2.01	0.10	0.58	1.17

Table 4. Statistical Analysis of Precipitation Rates from the MM5.

MM5 (hours)	Samples	RMSE (mm/h)	CC	Fcst Ave (mm/h)	Observed Ave (mm/h)
09	17	3.50	0.02	0.40	1.39
12	22	2.80	0.21	0.83	1.50
15	19	1.25	-0.13	0.35	0.78
18	19	2.86	0.20	1.46	1.22
21	16	1.57	0.33	1.24	0.70
>=24	22	0.94	0.19	0.70	0.41
Total	115	2.15	0.14	0.83	1.00

Tables 3 and 4 show the results of the precipitation rates. As expected, the CC are very low because of the wide disparity in rainfall prediction. This is also seen in the RMSE column, where both models show a high error. Overall, the sample size for the hourly data is rather small; however, there are interesting trends noted in these data. For both the BFM and MM5, the initial time period shows the lowest forecasted precipitation rates. According to Dudhia, the precipitation may take several model time steps between production and when it finally reaches the ground. In the BFM, this may be a function of slow moistening of the atmospheric column and lower mixing ratio, cloud fraction, precipitation rate, along with a high evaporation rate (*18*).

After the initial forecast period, the BFM precipitation rates are nearly constant through the 24-h model run. Additionally, the observed precipitation shows little variation through the data. This

is not the case with the MM5 output, which shows more fluctuation in both the forecast averages and observed averages. Of great interest is the trend in the MM5, where the precipitation rates are less than the observed precipitation rates through the first 15 h of the model runs and then suddenly changes at the 18-h period when the forecasted precipitation becomes greater than the observed rates. The significance of this trend and its cause is uncertain because of the small data sample.

6.3 Precipitation Type

An interesting question is: Does the precipitation type have any influence in the rainfall rates, snowfall rates or total amounts? In this study, the routine developed at ARL is used to determine if the precipitation will reach the surface as rain, snow, freezing rain, or some mixture of rain and snow. The routine is implicit, so it is run as part of the post-processor from the BFM and MM5. Using this method, only the lowest 10,000-ft above ground level (AGL) is used, since most stratiform precipitation falls from clouds below that level and the temperature is almost always below 0 °C in typical wintertime precipitation above that level. Listed below are some of the key assumptions of the precipitation-type software:

- Uses the forecasted wet bulb temperatures rather than temperature.
- Goes vertically from surface and counts layers above and below 0 °C.
- If all layers are below freezing, then precipitation will be snow. If all layers are above 0 °C then precipitation will be rain at the surface.
- Freezing rain is forecasted when some layer above the surface is above 0 °C and the surface is at 0 °C or less.
- Calculates the depth of the elevated warm layer, which will help determine if falling snow will melt.
- Calculates the near surface-layer average temperature to know the depth of any warm or cold layers near the surface.
- Does checks to see if snow will melt before reaching ground or rain will freeze at the surface.
- If the routine finds a borderline case between rain and snow, it becomes a “mixed” case.

During the winter season of 2003, nearly 500 surface observations were collected to coincide with areas where the BFM and MM5 were run. The emphasis in the BFM was for all forecasts less than 12 h and for the MM5 from 9 to 24 h. In table 5, the results of the precipitation type study from the BFM are shown, while table 6 shows similar results from the MM5.

Table 5. BFM Precipitation-Type Forecasts (Horizontal) and Observations (Vertical) for all Forecast Hours 499 Samples).

Fcst/Obs	**None**	**Rain**	**Snow**	**Freezing Rain**	**Mixed**
None	249	36	21	0	0
Rain	49	51	5	0	0
Snow	13	14	38	0	1
Freezing Rain	8	5	2	0	1
Mixed	1	6	0	1	0

Table 6. MM5 Precipitation-Type Forecasts (Horizontal) and Observations (Vertical) for all Forecast Hours (461 Samples).

Fcst/Obs	**None**	**Rain**	**Snow**	**Freezing Rain**	**Mixed**
None	218	67	15	0	3
Rain	20	55	1	0	0
Snow	13	8	44	0	3
Freezing Rain	1	6	0	1	0
Mixed	1	4	0	0	1

Tables 5 and 6 show encouraging results, especially in the snow forecasts. In 84 percent of the BFM snow cases, snow was forecasted, while 98 percent of the snow forecasts were correctly predicted in the MM5. There was a higher error in the rain forecasts, although the POD of rain was still 67 percent in the BFM and 75 percent in the MM5. However, it should be noted, the error of forecasting rain and having freezing rain occur is a function of the models not forecasting the surface temperature cold enough. Even an error of 0.1 °C can cause this forecast to be incorrect. As noted by Passner (*14*), the BFM tends to overforecast the surface temperature when the boundary layer is moist, thus it is not surprising to see 18 percent of the snow cases being forecasted as rain cases due to this high temperature bias. The MM5 has a slight bias to underforecast the temperature in moist environments, thus this cold bias helps to drive the MM5 surface temperature lower and results in a very high POD for snow forecasting. The main bias in the precipitation-type software is that too many rain forecasts are actually being observed as snow, freezing rain, or mixed precipitation.

The sample size for freezing rain and mixed precipitation was very small as only about 4 percent of all the precipitation observations were freezing rain and approximately 4 percent were mixed precipitation. As noted in the tables, the precipitation-type software rarely forecasts freezing rain or mixed precipitation, most likely because the models cannot achieve a detailed enough profile of the temperature and moisture.

A final area to investigate was how the precipitation rates varied with the precipitation type in each model. Table 7 shows the differences in the forecasted and observed precipitation rates for rain and snow with the BFM and MM5.

Table 7. Precipitation Rates and Precipitation Types for the BFM and MM5 (All Hours).

Model and Precip Type	**Samples**	**RMSE (mm/h)**	**Forecast Avre (mm/h)**	**Observed Ave(mm/h)**
BFM Snow	34	0.80	0.54	0.75
BFM Rain	93	1.32	0.68	1.54
MM5 Snow	31	0.84	0.37	0.58
MM5 Rain	63	2.70	1.04	1.31

The results in table 7 show that precipitation rates and observed rates are significantly lower for snow than for rain. Both models underforecast the snowfall rates, with the BFM underforecasting snowfall rates by 28 percent while the MM5 underforecast the snowfall rates by 36 percent. The BFM does have a more significant error in rainfall rates with an error of 56 percent in the rates while the MM5 rainfall rates are underforeacsted by 21 percent. The rainfall rates are higher than snowfall rates because there is more available liquid water in the atmosphere and the mixing ratio values are higher.

7. Summary and Discussion

This study was designed to investigate the precipitation rates, precipitation amounts, and precipitation types forecasted from two mesoscale models, the BFM and MM5. A description of how precipitation is formulated in each model helps to enhance the understanding of how these factors influence the model output. The BFM stratiform precipitation rates depend on the precipitation rate itself and the evaporation of the precipitation as it falls through the atmospheric layers. The most significant terms for the precipitation rate is the cloud liquid water of the layer, the cloud fraction of the layer, the coefficient for cloud water content at which the release of

precipitation becomes efficient, and the coefficient for the conversion rate of cloud particles to precipitation size. The evaporation rate in the BFM depends on the relative humidity of the layer, the cloud fraction, the precipitation rate for the column, and a constant derived by Sundqvist (*15*).

In the MM5, the stratiform precipitation routine is an explicit scheme, where the scheme is activated when grid-scale saturation is reached. There is an explicit treatment of cloud water, rain water, snow, and ice along with feedback to the temperature and moisture field along with the radiation scheme. The MM5 contains a microphysics package known as the mixed-phase Reisner microphysics package, which builds upon the simple ice routine by permitting supercooled water below 0 °C and has a gradual snow melt as it falls. Additionally, unmelted snow can exist above 0 °C. The value of the mixing ratio is used in the final fall term in the MM5. This fall term is the actual precipitation that reaches the ground.

The statistical evaluation of the models provided many useful hints on how to improve and upgrade the model. The BFM is underforecasting precipitation rate by nearly 50 percent, while the MM5 is underforecasting precipitation rates by 17 percent for the overall model sample. The MM5 has an interesting trend, where the model underforecasts rates by 43 percent through 15 h and then overforecasts the rates by 156 percent from 15 to 48 h after model initiation. Both models produce lower precipitation rates in snow than rain, and it was found that the models rarely produce snowfall rates (liquid equivalent) greater than 1.00 mm/h. The BFM error is logical, given the model's dry bias and the problems with excessive evaporation below cloud base; however, the trends in MM5 precipitation rates are more complex since it contains a microphysics package with many assumptions about cloud nuclei sizes, density, and nuclei amounts.

The most vital role of the precipitation rates is that they influence the prevailing surface visibility in the post-processing software. Knapp developed regression equations based on 2790 surface observations using two types of equations; one with a known ceiling but no precipitation falling and another with a ceiling along with precipitation. Passner noted that model biases were influencing visibility forecasts and that the equations Knapp formulated were not working well with the BFM and MM5 output. To compensate for these results, rainfall and snowfall rates were used to help determine precipitation. As an example, when snowfall rates of 1.75 to 2.54 mm/hr were produced by the model, the forecasted visibility was one mile (*19*, *14*).

Table 8 shows the performance of the models under different precipitation conditions, which are the result of a visibility test.

Table 8. BFM and MM5 Visibility Errors Based on Observed Winter Weather in 2003.

Model/ Obstruction	Forecast Ave (miles)	Observed Ave (miles)	Mean AD	Samples
BFM No Precipitation	7.68	9.67	2.18	151
MM5 No Precipitation	8.14	9.67	1.68	198
BFM Fog	5.50	3.50	4.00	62
MM5 Fog	5.68	3.68	3.30	50
BFM Rain	5.76	4.80	3.01	112
MM5 Rain	5.32	4.90	3.10	83
BFM Snow	5.49	1.97	3.90	63
MM5 Snow	6.08	2.45	4.46	72

The results in Table 8 show the model visibility forecasts are accurate when no precipitation is falling. When fog, rain, or snow is observed, the models overforecast visibility in all three cases. The fog cases are using the original visibility equations from Knapp (*19*); however, the rain and snow cases are based on the adjustments made for precipitation rates. The mean AD is generally the same in all three cases; however, the most significant error appears to be with the snow cases, which are overforecasted on average by 3.6 miles.

In 74 percent of the snow cases, the observed surface visibility was less than 2 miles; however, the average snowfall forecast in this study was 5.75 miles. A future step will be to lower the snowfall rates and the forecasted visibilities since the models are not able to physically produce the precipitation intensity that is often observed. The other major change in the BFM will be to use the 70-minute conversion rate, which should enhance the rainfall and snowfall rates. These two techniques should make a dramatic improvement in the post-processed visibility routine. Additional testing will be conducted to evaluate how these changes work with an independent data set in a variety of winter conditions. Additional evaluation of precipitation forecasts must also be completed with small-scale models such as a 5-km MM5 to see if the forecast are sensitive to grid resolution.

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Acronyms

AD	absolute difference
AFWA	Air Force Weather Agency
AGL	above ground level
ARL	Army Research Laboratory
BFM	Battlescale Forecast Model
CC	correlation coefficient
CNE	correct non-event
CSI	critical success index
FAR	false alarm rate
GMDB	Gridded Meteorological Database
GriB	gridded binary form
HOTMAC	Higher Order Turbulence Model for Atmospheric Circulations
IWEDA	Integrated Weather Effects Decision Aids
IMETS	Integrated Meteorological System
mbar	millibar
MM5	Mesoscale Model Version 5
NOGAPS	Naval Operational Global Atmospheric Prediction System
POD	probability of detection
RMSE	root-mean square error
TDAs	Tactical Decision Aids
TSS	true skill score
UTC	universal time coordinated

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